NBSIR 81-2277

Control Strategies for Energy Conservation -- A Case Study of the Materials Building, National Bureau of Standards

James Y. Kao
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Building Equipment Division
Center for Building Technology
U.S. Department of Commerce
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

PREFACE

This study was funded by the Plant Division of the National Bureau of Standards (NBS). It is the objective of the NBS Plant Division to determine the annual energy savings that may be realized from implementation of new air handling system control strategies and thus to plan air handling system control retrofits Bureau wide. The retrofit of these controls will aid the Plant Division in obtaining their 20 percent reduction in energy consumption by FY 85 compared to FY 75, as required by the Department of Energy's Ten Year Energy Conservation Buildings Plan. The Plant Division presently has a boiler improvement study under way to determine the heating plant efficiency, and is planning to evaluate the refrigeration plant performance in the near future. Verification of the predicted results of some of the control strategies in this study is currently being prepared and will be evaluated in the future. The NBS energy monitoring and control system will be used to collect building energy consumption data and to implement enthalpy control and system shutdown strategies.

The control strategies selected in this study and the input data for the calculations were determined jointly by the Plant Division and the authors. The authors wish to express their appreciation to Christopher Conley and Kendall McDaniel of the Plant Division for their assistance.

ABSTRACT

The BLAST-2 computer program is used to investigate various heating, ventilating and air conditioning control strategies and their combinations to reduce the energy consumption of a laboratory building located at the National Bureau of Standards Gaithersburg site. The techniques of modeling the building load and air system performance are explained. The results are presented and discussed. Control strategies investigated include dry-bulb and enthalpy economizer cycles, resetting supply air temperatures by outside temperature and zone demand, shut-down of fan systems selectively, and converting interior systems to VAV systems. By combining the various control strategies, eight percent, twenty-nine percent and eight percent of heating, cooling and fan energy respectively may be saved.

Keywords: building energy analysis; computer modeling, control strategies; controls, energy conservation for non-residential buildings; load calculations.

CONVERSION FACTORS TO METRIC (SI) UNITS

Physical Quantity	Symbol	To Convert From	To	Multiply By
Length		ft	m	3.048×10^{1}
Temperature	T	°F	°C	$T_C = (T_F - 32)/1.8$
Volume Rate of Flow	V	CFM	m^3/s	4.719×10^{-4}
Coil Capacity	Q_s	Btu/hr	J/s	2.931×10^{-1}
Energy		Btu	J	1.055×10^{3}

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1. INTRODUCTION

The Gaithersburg site of the National Bureau of Standards (NBS) has over 2.2 million square feet of floor space. Used mainly for office and laboratory functions, most of the buildings were constructed in the 1960's. Several years later, during the early 1970's, major efforts were made to reduce the energy consumption of the building heating, ventilation and air conditioning (HVAC) systems [1]*. Lighting reductions, office-space HVAC-system shut-downs, space thermostat adjustments, and raising the air-handling system discharge-air temperatures resulted in approximately a 12 percent electricity reduction and 18 percent heating fuel reduction. A further overall energy reduction of approximately 5 percent [2] was made during FY 1980 (using FY 1975 as a base). This reduction was attributed to the implementation of the Emergency Building Temperature Restriction [3], shutting down of additional mechanical equipment during non-occupied hours, and the implementation of new HVAC control systems.

Several of the HVAC control strategies compared in this study were previously evaluated at NBS. During the mid-1970's, a computer program and bin method were used to predict the energy savings of enthalpy control, supply-air temperature reset, and shutting down of office spaces during non-occupied hours.

As a continuing effort in energy conservation at NBS, the HVAC control strategies in the General Purpose Laboratory (GPL) buildings are examined in this study. At this site, there are seven GPL's with similar constructions and physical dimensions as well as similar HVAC-system arrangements. The energy conservation control strategies and energy saving predictions for one laboratory building should be applicable to all the others, with minor modifications. The building chosen for this study is Building 223, also known as the Materials Building.

One of the dominant factors influencing the amount of energy consumption in non-residential buildings, such as the NBS laboratories under study here, is the performance of automatic temperature and humidity controls that regulate the operation of the HVAC systems. Although these controls generally include the heating and cooling generation, as well as the air systems to deliver the desired heating and cooling energy to the occupied spaces, the present study is limited to the consideration of the latter only. At NBS, the heating and cooling media are generated in a central plant and are distributed to individual buildings through underground steam and chilled water pipes. This study investigates some of the control strategies which may be used for the air handling systems inside the Materials Building and therefore, the energy amount predictions are the energy required to be delivered at the building boundary.

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*Figures in brackets indicate references on page 30.

2. BUILDING AND BLAST IMPLEMENTATION

2.1 BUILDING DESCRIPTION

The Materials Building is a three-story building, 385 feet long, and 105 feet wide, with the long axis along the true east-west direction. The result of this orientation is that all windows are facing either north or south. The building is of heavy reinforced concrete construction. The building is divided into interior and perimeter spaces. The interior rooms are used mainly for laboratories and the perimeter rooms are generally used for offices. Six air-handling units serve the interior zones, and an additional four air-handling units serve the perimeter offices, two units each for the north and south sides. Constant volume HVAC systems are located on the attic floor. The air-handling units are composed of air filters, steam preheat coils, steam humidifiers, chilled water cooling coils, supply-air fans and return-air fans. A simplified building floor plan and cross section are shown in figure 1.

A constant volume of air is supplied to the rooms with reheat provided by hot water reheat coils. The reheat coils for the laboratories are of the duct type, and those for the perimeter offices are of the induction type with the induction units located under the windows. There are over 80 laboratory exhaust fans discharging air through the roof. Steam at 150 psig and 42°F chilled water are supplied from the central plant. Closed-loop hot water is generated inside the building from steam.

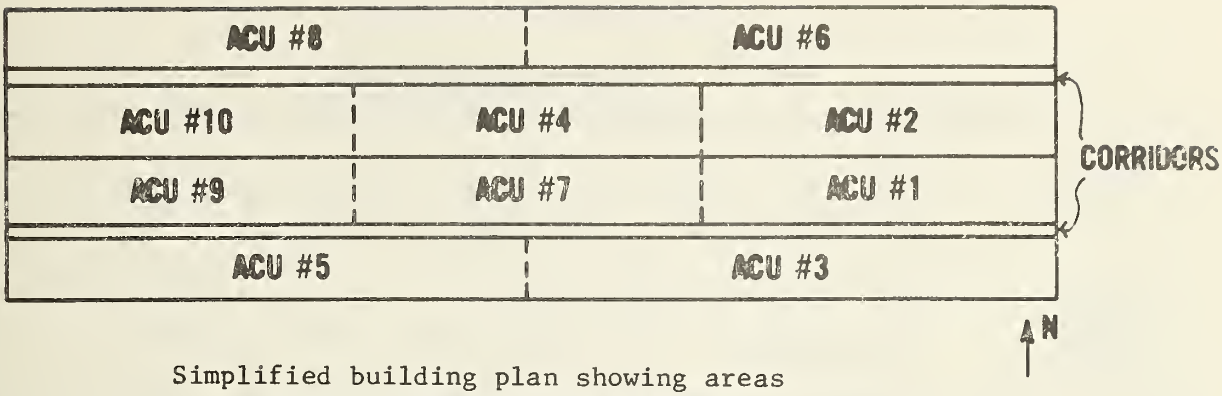
2.2 BLAST MODELING

The computer program BLAST-2 [4] was used to calculate the building energy consumptions. BLAST, one of the public-domain building energy analysis programs, is recognized as representing the state-of-the-art. The basic design is to model each room as a single office or laboratory module, rather then to lump large sections together without separating partitions. These individual-space modules are to provide for radiation exchange between the walls, floor and ceiling of the module. Multipliers ("zone-multipliers" in the terminology of BLAST) then establish the correct number of spaces for each air handling system. The six interior (laboratory) air handlers were combined into a single interior air handler for this analysis, and the four perimeter (exterior offices) air handlers were modeled as in the real building.

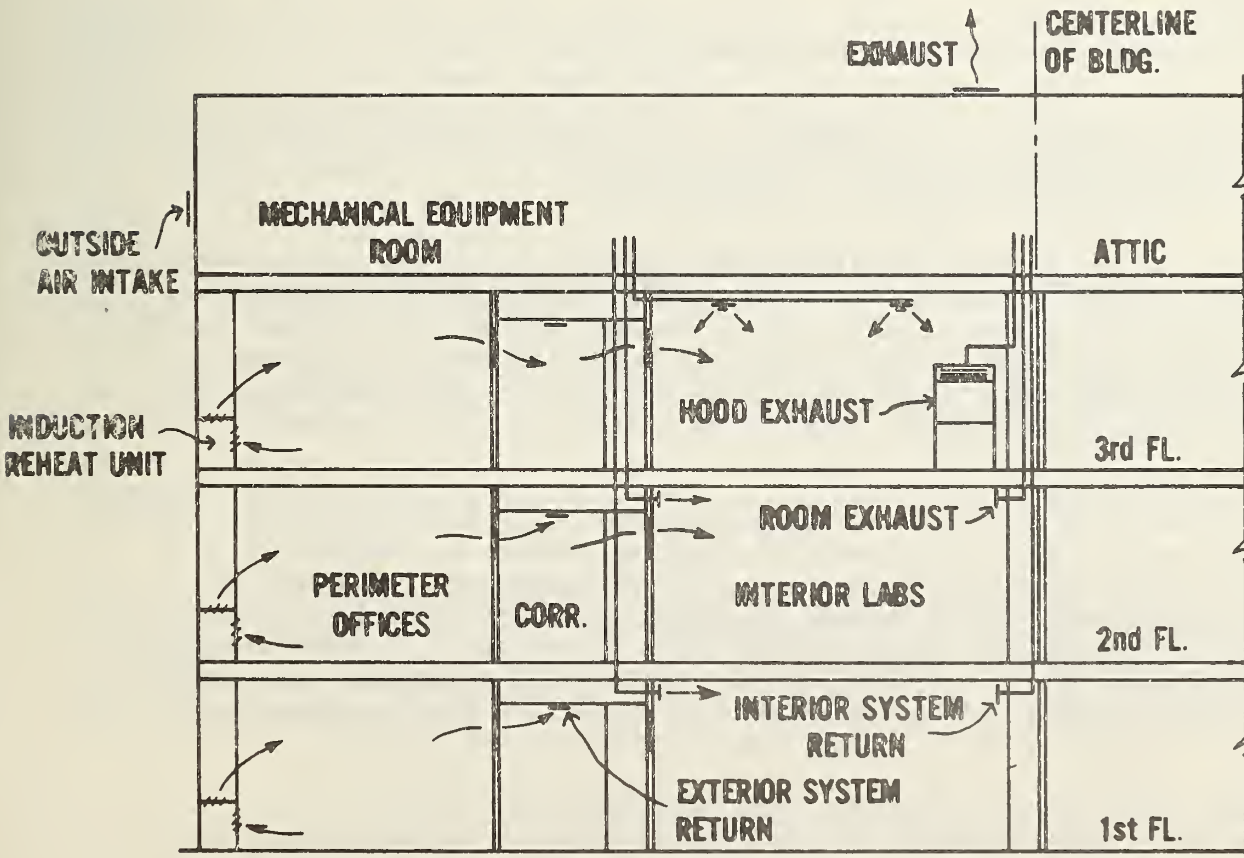
The interior air handler of the model has 84 general purpose and 96 more critical laboratory spaces, a total of 180 module spaces, and is designated system twenty in this report. The four exterior air handlers are designated systems three, five, six, and eight, and serve 36, 45, 47, and 38 offices respectively.

A single BLAST plant simulation supplies heating, humidification and cooling to all of the air handlers, so as to summarize the overall steam and chilled water energy requirements for the building.

People, lights, and electrical equipment were scheduled so as to approximate the sensible and latent effects resulting from these sources of internal heat



Simplified building plan showing areas
served by air handling systems



Typical cross section of building

Figure 1. Simplified building plan and cross section

Table 1. Internal Load Profiles

Hours									
From	5	6	7	8	9	10	11	12	
To	6	7	8	9	10	11	12	13	
People	.1	.1	.2	.8	1	1	1	.8	
Lights	.2	.2	.2	.5	1	1	1	1	
Equipment	.2	.2	.2	.2	1	1	1	1	
Hours									Nights
From	13	14	15	16	17	18	19	20	and
To	14	15	16	17	18	19	20	21	Weekends
People	1	1	1	1	.6	.2	.1	.1	.0
Lights	1	1	1	1	1	.2	.2	.2	.2
Equipment	1	1	1	.4	.2	.2	.2	.2	.2

gains, as shown in table 1. The numbers in the table are scaling factors, by which the peak magnitudes of people, lights and equipment for each space are multiplied to determine the hourly internal loads.

Weather data for the energy analysis requires hourly information about weather parameters. A Typical Meteorological Year (TMY) weather file for Washington, D.C. was used in the present study. TMY files are composed of "typical" months selected from SOLMET files for different years, and include solar intensity data. The year 1979 determined the position of the sun for any particular day, and the weather file established the location as latitude = 39.0, longitude = 77.7 degrees.

Five design days were also used during certain tests of the BLAST models. These are not the sort of design day used for sizing equipment, but rather are used to see how a building performs under a variety of conditions, as shown in table 2. Temperatures are in degrees Fahrenheit, and the wet-bulb temperature corresponds to the highest dry-bulb temperature of the day. At lower dry-bulb temperatures, BLAST holds the same humidity ratio until saturation is reached, and then tracks downward along the saturation curve (and back up along the same path). Design day DD5 is cloudy; the rest have clear skies.

BLAST heating and cooling capacities were established as follows: for a particular air handling system, the top floor receives 20 percent more supply air than the two lower floors. These supply-air quantities established the cooling capacities for each space according to the formula $Q_s = 1.085 \times V \times (T_{room} - T_{supply})$, where T_{room} and T_{supply} are the room and supply air temperature in °F dry bulb, V is the supply air volume in cubic feet per minute, and Q_s is the supply air capacity for those particular temperature conditions in Btu/hour. The heating capacities were considered adequately sized, so that the

Table 2. Design Days

Design Day Name	Temperature, °F High	Low	Wet-Bulb	Date
DD1	91	71	77	21 July
DD2	78	58	65	21 April
DD3	62	42	52	21 April
DD4	33	13	27	21 January
DD5	13	13	11	21 January

space temperature would not drop below the local heating setpoint temperatures during non-shutdown hours.

During perimeter system night shutdown, it was considered that without the induction air the heating setpoint temperatures would not always be maintained, so that the resulting space temperature drift was simulated with a ramp control, fully on at 55°F and fully off at 65°F. The fully on heating capacity for use during system shutdown was set at the rate required to maintain the space at 65°F over the whole TMY year. This resulted in a simulated space temperature drift during night shutdown that went down to approximately 57°F with the design day DD5, and reached a low of approximately 58°F on the TMY-year weather file. During the office hours on design day DD1 with 60°F supply air temperature, the space temperature varied between 72°F and 75°F in the third floor perimeter offices on the south side of the building and between 74°F and 77°F in the north side third floor perimeter offices. During the night shutdown, the space temperature drifted to approximately 81°F and 82°F, respectively, in these offices. There was, of course, no cooling capacity available during the time when an air-handling system was shut down. The higher temperature in the north offices than the south offices was caused by lower supply air quantities to the north side than to the south side.

Each of the air-handling systems has a cooling coil designed for NBS conditions (rather than making use of the BLAST default coil). Other model system characteristics include steam humidification to 30 percent RH, a 1°F throttling range in the cold deck control, steam preheat in the mixed air chamber, and a 3 inch supply fan pressure rise.

3. CONTROL STRATEGIES AND MODELING

3.1 CONTROL STRATEGIES

A simple constant-volume, fixed discharge-air temperature (not necessarily the same temperature for all air-handling systems), fixed outside air amount, and space controlled reheat temperature model was used as a base case for energy consumption comparisons. The control strategies tested including raising the cooling coil discharge air temperature, adding dry-bulb return air economizer control, adding enthaply economizer control, resetting the perimeter system supply air temperature seasonally or by outside air temperature, converting interior systems to variable air volume (VAV), controlling interior system supply air temperature by zone demand, selectively shutting down perimeter systems during non-office hours, and different combinations of these strategies. Finally, an architectural retrofit, using double-glazed windows for the single-pane windows, was modeled for the base case. The modeling of some of these strategies is described in detail below.

Case 1. BLAST Base Case

For the basic BLAST base case, as few BLAST options as reasonable were used, so that the effect of existing as well as new control options could be studied. Hence, the case 1 configuration has a constant volume, fixed outside air quantity (no damper control), 30 percent minimum relative humidity in the space, with the off-coil air temperature of the cooling coils at 57°F for interior systems and 60°F for perimeter systems. Complete input data of the base case may be found in the Appendix.

Case 2. Raising Perimeter System Supply Air Temperature to 65°F in Winter

This is the same as case 1, except that the supply air (SA) temperature for perimeter systems is set at 65°F during the months of November through April. The BLAST input form is

```
COLD DECK TEMPERATURE = 65;.
```

Cooling and reheat energy should both be saved, since the cold supply air is closer to the room temperature. However, depending on the outside air conditions, more steam may be required to attain the required space humidity.

Case 3. Dry-Bulb Economizer for All Air-Handling Systems

The BLAST input form is

```
MIXED AIR CONTROL = RETURN AIR ECONOMY CYCLE;.
```

This is a damper control in which the outside air (OA) dampers range between a minimum established by the exhaust air (EA) quantity and a maximum of 100 percent. Return air and outside air are mixed to achieve mixed air (MA) at the cold deck dry bulb temperature, if possible.

Case 4. Dry-Bulb Economizer with Perimeter Winter Supply Air Temperature at 65°F

The perimeter system supply air temperature is seasonally adjusted as in case 2. This is a combination of cases 2 and 3.

Case 5. Enthalpy Economizer for Perimeter Systems

An enthalpy test permits dry-bulb control of the OA dampers in those cases where the OA-enthaply is less than that of the return air. The enthalpy test decides whether minimum or 100 percent outside air should be admitted. If the outside air enthalpy and dry-bulb temperature are less than those of the return air, the outside air damper is controlled to give mixed air temperature not lower than that of the supply air. The BLAST input form is

MIXED AIR CONTROL = ENTHALPY ECONOMY CYCLE;.

Case 6. All 10 Systems have Enthalpy Economizer

Similar to Case 5, all 10 systems add enthalpy economizer cycle to the base case.

Case 7. Perimeter System OA-Reset

The BLAST input form is

COLD DECK CONTROL = OUTSIDE AIR CONTROLLED;
COLD DECK CONTROL SCHEDULE = (65 AT 65, 60 AT 66);.

The supply air temperature is 65°F when outside temperature is 65°F and below, and changes to 60°F when outside is 66°F and over. It simulates a flip-over type of supply air temperature control for the perimeter systems. The one degree (65°F to 66°F) is to allow for the BLAST throttling range in the cold deck control. An error in the BLAST program code (previously uncorrected even at CERL) was discovered during this study and was corrected by NBS.

Case 8. Perimeter System OA-Reset

This is similar to Case 7, except that a linear reset schedule is established between two sets of outdoor air and supply air temperatures. In this case, the supply air temperature is set at 65°F when the outside is at 40°F and below, the supply air is at 60°F when the outside air is at 80°F and above. In between 40°F and 80°F outside temperature, the supply air is controlled linearly between 65°F and 60°F. The BLAST input form is changed for case 7 to

COLD DECK CONTROL SCHEDULE = (65 AT 40, 60 AT 80);.

Cases 9, 10, and 11. Perimeter Systems Shut-Downs During Non-Office Hours

These cases are for shutting down the perimeter systems and toilet exhaust fans during non-office hours (nights and weekends). Due to the requirement for constant laboratory exhaust air, and to the heating of the reheat-induction units during heating seasons, more complicated modeling schemes are needed. These will be discussed later in this section.

Case 12. Interior Systems Converting to VAV

The supply air volume is controlled to maintain 65°F in the non-critical laboratory spaces. That is, there is a quite narrow throttling range for the zone dampers to move from fully open to minimum positions. In this case, only the non-critical laboratories are converted to VAV systems.

Case 13. Interior System VAV Adding Enthaply Economizer Cycle

This is similar to case 12, adding enthalpy economizer cycles to the interior systems.

Case 14 to 17. Interior System Supply Air Temperature Reset by Zone Demand and Selected Combinations

Instead of converting interior systems to VAV as assumed in case 12, the interior non-critical laboratories may be retrofitted to have varying discharge air temperature which is set by the most demanding zones. Case 14 is a single strategy case, to vary the supply air temperature from 50°F to 60°F. Case 15 is case 14 modified by a seasonal change, reset supply air temperature from 50°F to 60°F between May 1 and September 30, and from 50°F to 70°F between October 1 and April 30. Case 16 is similar to case 14, adding enthalpy economizer cycles to all systems. Case 17 is similar to case 15, also adding enthalpy economizer cycles to all systems. The reason for having the seasonal reset schedules in cases 15 and 17 is to achieve maximum reset benefit yet to avoid unacceptably high space humidity during the summer seasons.

Case 18 and 19. Comprehensive Combined Control Strategies

Case 18 combines the perimeter system supply air reset to 65°F when outside is 65°F and below, and to 60°F when outside is 66°F and above (as in case 7), shutting down ACU #6 and the toilet-exhaust fans during non-office hours (as in case 9), interior system supply air temperature reset by zone demand from 50°F to 60°F (as in case 14), and all systems under enthalpy economizer cycle (as in case 6). Case 19 is similar to case 18 except that the perimeter supply air temperature reset is changed to 65°F when outside is 40°F and below, to 60°F when outside is 80°F above, and controlled linearly between the 60°F and 65°F conditions (as in case 8).

Case 20. Base Case with Double-Glazed Windows

This is the only case for which architectural retrofit was involved in this investigation.

3.2 AIR BALANCE

In order to obtain the best energy consumption calculation results, it is important that the actual building operating data, including air balance data, be used in this kind of study. Therefore, the system air balance data had been measured by a combination of tracer gas and pitot tube techniques, as shown in figure 2. Tracer gas measurements were used to find the ratio of supply to return air (SA/RA), and pitot measurements measured return and exhaust air quantities. Table 1A shows those data as determined by these techniques. The return and exhaust columns show the directly measured data, and the supply and outside air quantities are derived by the equations

$$SA = (SA/RA)RA, \text{ and}$$

$$OA = ((SA/RA)-1)RA$$

The outside and exhaust air totals differ by four percent of the supply air total, which is a measure of the possible accuracy of these results. Since the tracer gas is believed to provide quite accurate results, the exhaust data were considered less significant in developing the magnitudes used in BLAST, as shown in table 1B.

The building is assumed to be balanced in the baseline condition. That is, for the building as a whole, the net infiltration is zero, and the total of the exhaust air and return air exactly equals the supply air to the spaces of the building. Thus the outside air is equal to the exhaust air.

$$SA = RA + EA \text{ , } OA = EA$$

This assumption is conservative in that additional infiltration might result in additional energy consumption, and is consistent with the observation that in fact the building pressure varies from neutral to very slight exfiltration.

Within the building, the individual space air handlers are not balanced. For the exterior systems, there is no exhaust, and the supply air exceeds the return air with the excess conditioned air (CA) going to the interior systems:

$$SA = RA + CA \text{ , } EA = 0.$$

For the interior systems, this excess conditioned air plus the interior supply air is equal to the return air plus the exhaust air:

$$SA + CA = RA + EA.$$

The exhaust air includes the air taken by laboratory hoods, general exhausts, and toilet exhausts. No exhaust is assigned to the exterior systems.

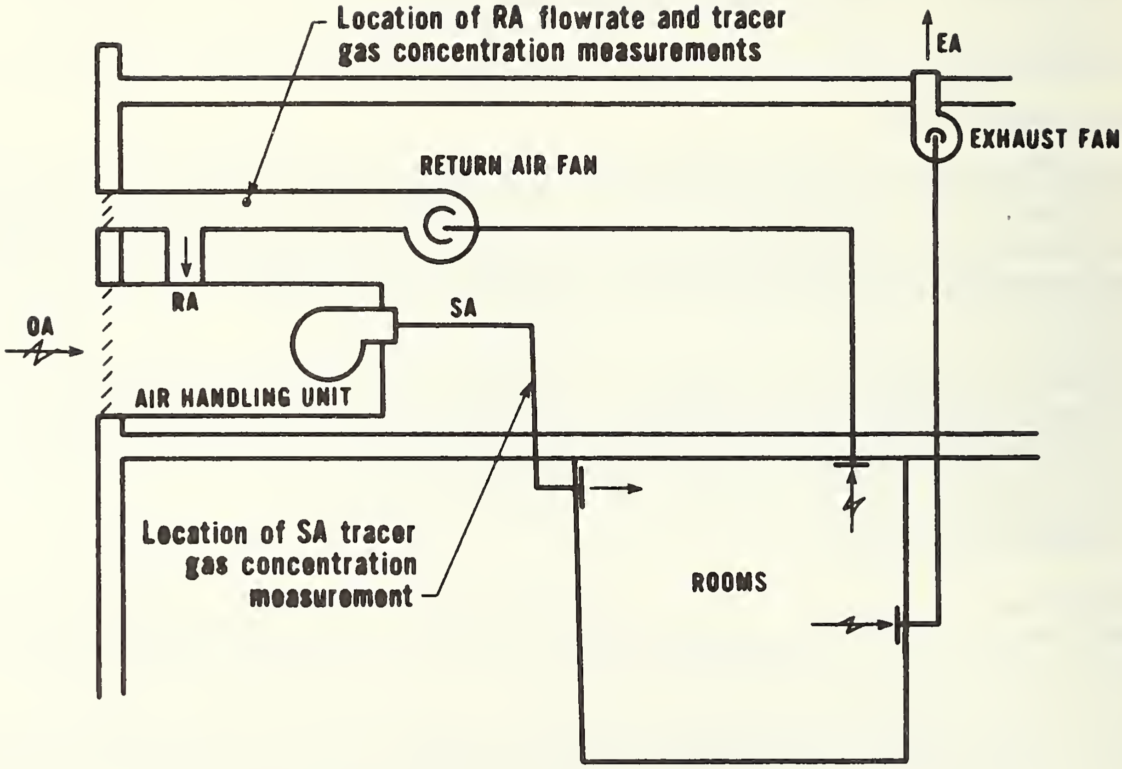


Figure 2. Measurement of air quantities. Tracer-gas determines ratio SA/RA; EA and RA are measured directly.

Table 1A. Available Data on Real Air Balance

	SA/RA	Return	Exhaust	Supply	Outside
		cfm	cfm	cfm	cfm
Labs	1.853	46 870	62 300	86 860	39 990
Toilets	---	0	2 250	0	0
ACU-3	1.548	7 630	0	11 800	4 170
ACU-5	1.862	7 490	0	13 940	6 450
ACU-6	2.008	5 400	0	10 840	5 440
ACU-8	1.572	5 850	0	9 200	3 350
		73 240	64 550	132 640	59 410

Table 1B. Air Balance for BLAST

	Return	Exhaust	Supply	Outside
	cfm	cfm	cfm	cfm
Labs	46 870	57 160	86 860	39 990
Toilets	0	2 250	0	0
ACU-3	7 630	0	11 800	4 170
ACU-5	7 490	0	13 940	6 450
ACU-6	5 400	0	10 840	5 440
ACU-8	5 850	0	9 200	3 350
	73 240	59 410	132 640	59 410

Note: The air quantities under the outside columns do not add up to the total quantities due to round-offs.

In the BLAST model, the program parameters to be input are the supply and exhaust air volumes, and BLAST derives the return air and outside air quantities. For the exterior systems, the excess conditioned air is designated exhaust air, and the actual supply air volume is used. This forces an exterior system to condition an equal quantity of outside air, and again we have

$$SA = RA + EA \text{ , } OA = EA$$

For the interior systems, the excess conditioned air is exhausted without further energy transfer, so the measured outside air quantity is designated exhaust air, and again the actual supply air volume is used.

These concepts and assumptions are illustrated by figures 3, 4, and 5.

3.3 SYSTEM SHUTDOWN MODELING

Several of the energy conserving strategies considered involve shutting down the fans for one or more of the perimeter systems during nights and weekends. Such a shutdown here includes turning off the toilet exhausts, and may also involve switching one or more of the remaining perimeter systems to 100 percent outside air in order to have satisfactory laboratory exhaust. Thus a shutdown may cause changes in the air balance of the building, relative to the initial assumption that the base case building is balanced.

In the BLAST model, such changes in air balance were considered to result in changes in the quantity of system outside air, and were applied as an increase or decrease in the exhaust air of the interior (laboratories) system so that the outside air and exhaust air remain exactly balanced. That is, it was assumed that an increase in outside air came in through the systems, rather than as infiltration, and required energy to reach space conditions. Similarly, a decrease in outside air was assumed to decrease energy consumption.

As described above, there are two view points from which to consider the air balance data. Quantities relevant to both points of view are presented in table 2. Case 1 shows a repeat of the data from table 1B, and follows the same format. The return air quantities correspond to the data for the real building return air fan -- the total of the air returned. Similarly, the exhaust air and supply air columns correspond to data for the real building. The column "outside air" has a dual function: it is the real-building estimate of outside air, and it is also the BLAST model data for exhaust air.

Cases 9, 10, and 11 are the system shutdown cases. The toilet exhausts are off in each, and 100 percent outside air is used for those perimeter air-handling units that are in cases 10 and 11. The resulting assumptions about air balance for these cases are also shown in the table.

BLAST does not easily model a system shutdown for a building operating under NBS conditions. The system changes in air balance described above could not be modeled in a single computer run, since for each space the supply and return air quantities are input only once, and stay the same year round (except for VAV).

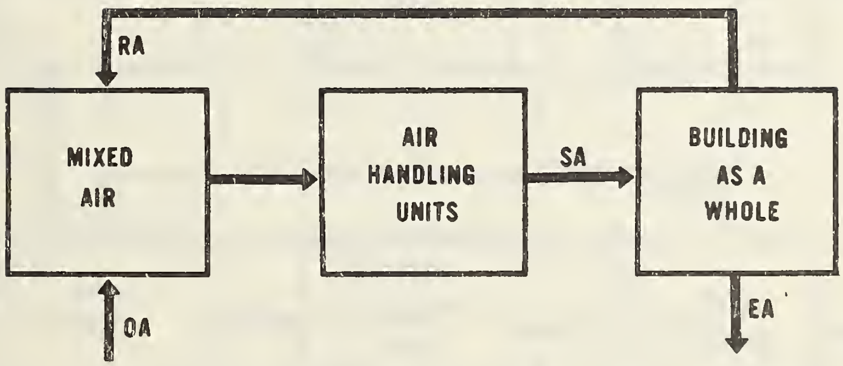


Figure 3. Air balance assumption

FOR THE BUILDING AS A WHOLE, BALANCE IS ASSUMED: NO RELIEF AIR, AND NO INFILTRATION.

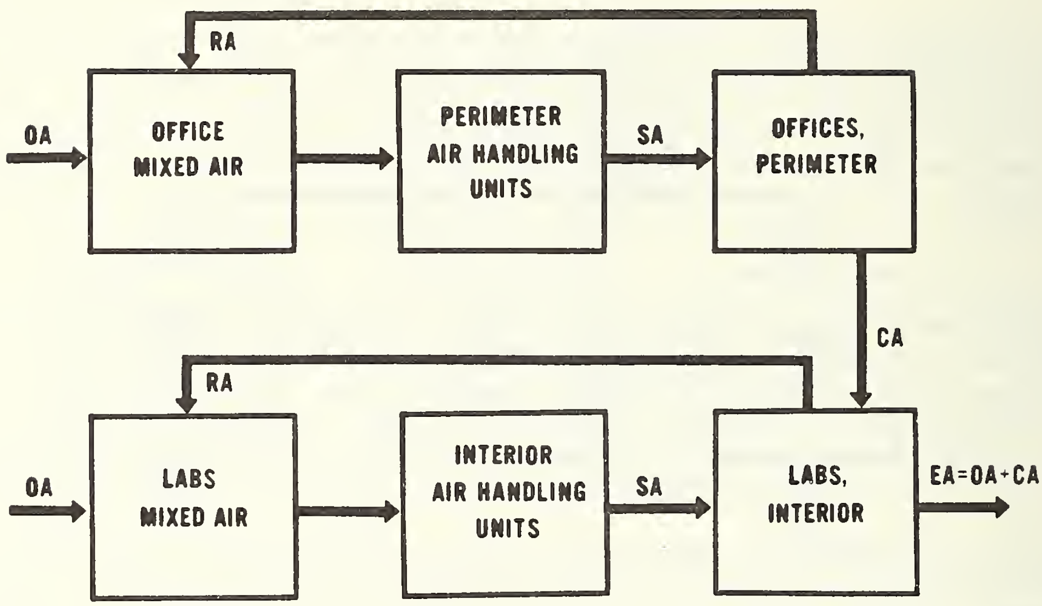


Figure 4. Air transfer between systems

WITHIN THE ACTUAL BUILDING, CONDITIONED AIR IS TRANSFERRED FROM THE OFFICE TO THE LABS.

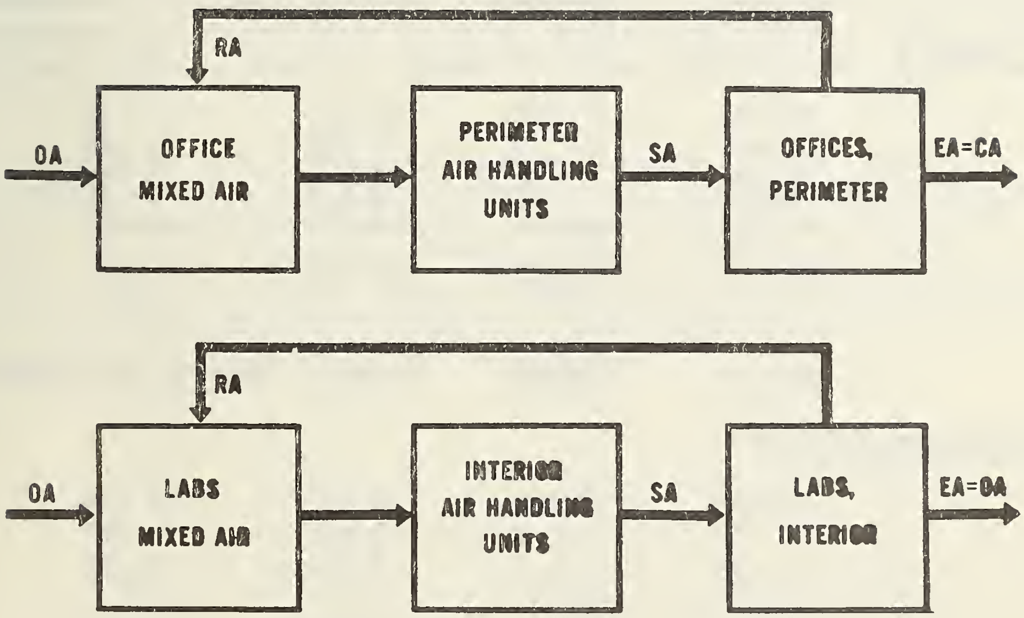


Figure 5. BLAST air balance

AS MODELED IN BLAST, THE EXCESS CONDITIONED AIR FROM THE OFFICES IS DESIGNATED EXHAUST AIR, AND THE LAB EXHAUST AIR IS REDUCED TO EQUAL THE LAB OUTSIDE AIR.

Table 2. Air Balance for BLAST During Shutdowns
(All Air Quantities are in cfm)

	Return (Real Bldg)	Exhaust (Real Bldg)	Supply (Both)	Outside and Exhaust (In BLAST)
BLAST Base-Case, Case 1				
Labs	46 870	57 160	86 860	39 990
Toilets	0	2 250	0	0
ACU-3	7 630	0	11 800	4 170
ACU-5	7 490	0	13 940	6 450
ACU-6	5 400	0	10 840	5 440
ACU-8	5 850	0	9 200	3 350
	73 240	59 410	132 640	59 410
	Return	Exhaust	Supply	Outside and Exhaust
ACU-6 Shutdown, Case 9				
Labs	43 680	57 160	86 860	43 190
ACU-3	7 630	0	11 800	4 170
ACU-5	7 490	0	13 940	6 450
ACU-8	5 850	0	9 200	3 350
	64 650	57 160	121 800	57 160
	Return	Exhaust	Supply	Outside and Exhaust
ACU's-3 and 6 Shutdown, Case 10				
Labs	52 840	57 160	86 860	34 020
ACU-5	0	0	13 940	13 940
ACU-8	0	0	9 200	9 200
	52 840	57 160	110 000	57 160
	Return	Exhaust	Supply	Outside and Exhaust
ACU's-3, 6, and 8 Shutdown, Case 11				
Labs	43 640	57 160	86 860	43 220
ACU-5	0	0	13 940	13 940
	43 640	57 160	100 800	57 160

Also, when the air is off, the window induction units are to continue to provide heat, although somewhat less efficiently as convection heaters, but BLAST would turn on the supply fan whenever such heat is supplied.

Thus it was necessary to devise a way to model the energy results of a shutdown option. This was done by combining the data from four computer runs: 1) the heat load during shutdown for the shutdown offices (a loads-calculation only); 2) heating and cooling during the shutdown hours for the rest of the building, in its normal (daytime) operation mode; 3) the same as run 2 with the parameters modified to the shutdown air balance, including the return fans off where a system went 100 percent OA; 4) The whole building heating and cooling energy, excluding shutdown offices during shutdown hours, based on the daytime operation mode air quantities. Note that runs 1, 2, and 3 operate only during nights and weekends. Run 1 provides correct data, but runs 2 and 3 include pulldown or startup errors when the systems are on at the beginning of the night. Fortunately, those errors are probably similar for the two runs, since they are subtracted one from the other to obtain the effect of the change in air balance. Finally, the pulldown or startup effects in run 4 are real: the shutdown offices will have drifted slightly in temperature in the summer, and cooling energy will be expended to return them to their daytime conditions. The building energy consumption is obtained by subtracting the results of run 2 from the sum of runs 1, 3, and 4.

An example of this procedure is given in table 3. The columns are labeled with the above run-numbers. Case 9 involves the shutting down of exterior system 6, as well as turning off the toilet exhausts. Note that although the data of runs 2 and 3 are relatively large, their differences are much smaller. Also, note how little energy is used for space heating (run 1). Most of the heating and cooling energy of a commercial building comes from cooling and reheating the circulating air, and from conditioning the outside air.

Table 3. Shutdown Example - Case 9

Month	Run 3	Run 2	(Run 3) -(Run 2)	Run 1	Run 4	(Run 3) -(Run 2) +(Run 1) +(Run 4)
Heating Energy (in 10^9 Btu)						
1	1.4250	1.3201	.1049	.0168	1.8080	1.9297
2	1.2179	1.1455	.0724	.0142	1.4984	1.5850
3	.8570	.7876	.0694	.0031	1.0927	1.1652
4	.4903	.4718	.0185	.0003	.7413	.7601
5	.3971	.3970	.0001	--	.6668	.6669
6	.3551	.3555	-.0004	--	.5818	.5814
7	.3684	.3693	-.0009	--	.5712	.5703
8	.3403	.3410	-.0007	--	.5663	.5656
9	.3914	.3918	-.0004	--	.6043	.6039
10	.4773	.4713	.0060	--	.7458	.7518
11	.6899	.6487	.0412	.0023	.9483	.9918
12	1.1458	1.0499	.0959	.0115	1.4016	1.5090
Σ	8.1554	7.7495	.4060	.0482	11.2265	11.6807
Cooling Energy (in 10^9 Btu)						
1	.0316	.0429	-.0113	--	.0819	.0706
2	.0348	.0443	-.0095	--	.0849	.0754
3	.1521	.1699	-.0178	--	.3129	.2951
4	.4232	.4446	-.0214	--	.7088	.6874
5	.8076	.8119	-.0043	--	1.2513	1.2470
6	1.2164	1.1982	.0182	--	1.8631	1.8813
7	1.7449	1.7007	.0442	--	2.5902	2.6344
8	1.4535	1.4234	.0301	--	2.2990	2.3291
9	1.2873	1.2673	.0200	--	1.8461	1.8661
10	.5328	.5512	-.0184	--	.8775	.8591
11	.2046	.2283	-.0237	--	.4613	.3926
12	.0354	.0491	-.0137	--	.1043	.0906
Σ	7.9242	7.9319	-.0076	--	12.4362	12.4287

4. RESULTS-DATA

The base case monthly heating and cooling energy consumptions for the interior, north and south perimeter systems are shown in tables 4, 5, and 6. The base case monthly heating, cooling and fan (including supply, return and exhaust fans) energy consumptions for the entire building are shown in table 7. These energy quantities, except for fan energy, are also plotted in figure 6. From these tables and figure 6, some of the energy consumption characteristics of the building may be seen, and possible opportunities for reducing energy consumption may be assumed. Of the total building heating energy, about 74.5 percent is consumed by the interior systems, 12.2 percent is consumed by the north systems and 13.3 percent is used by the south systems. For cooling, the distributions are 74.4 percent, 11.3 percent, and 14.2 percent, respectively. The large ratio of the interior system consumption to that of the perimeter system consumption indicates that emphasis of energy conservation controls should be placed on the interior systems. Of the 8.732×10^9 Btu interior heating consumption, 0.655×10^9 Btu is spent for preheat coil load, 0.957×10^9 Btu is used for humidifying load, yet 7.119×10^9 Btu is consumed by the reheat coils. This amounts to over 80 percent (81.5 percent to be exact) of the interior heating load being used by the reheat coils. For the whole building, over 60 percent of the entire heating load is spent in the interior reheat coils. Part of the high interior load is attributed to the larger interior floor areas (the ratio of interior to perimeter floor areas is 1.4 to 1), high equipment load, and the heat needed to raise the winter fan discharge air (around 60°F) to the space conditions; but the pure reheat effect on the energy consumption should be examined. This is also evident from table 4 and figure 6 that the interior system reheat energy consumption during the summer months is over $.53 \times 10^9$ Btu per month. The control strategy cases 12, 14, and 15 (interior system VAV conversion and reset by zone demand) should have major impact on the overall building energy reduction. On the other hand, cases such as 7 and 8 (perimeter reset) may not have large effects, on overall building percentage basis.

The yearly heating and cooling energies and fan electric energies of the building for the various control strategies are as tabulated in table 8. As described in the previous section, the base case has a fixed outside air quantity. The supply air temperature is set at 57°F for the interior systems and 60°F for the perimeter systems. Table 9 shows the normalized energy consumption for the same control strategies as listed in table 8 using the base case yearly energy consumption as one.

In all cases, when economy cycle control is added, either dry-bulb return air comparison or enthalpy comparison, the cooling energy is decreased but the heating energy is increased. The reason for the increase in heating energy is mainly due to the added humidifying load during the time when the dry outside air is introduced into the air-handling systems. Figure 7 compares the monthly humidifying loads for the base case and case 6 (enthalpy economizer cycle). The highest humidifying load occurs in January, but the highest increase between the two cases occurs in March and April. Of the yearly total heating energy, 11.2 percent is consumed by the humidifiers in the base case while 15.5 percent is used in the case with enthalpy control. Therefore, it is feasible to minimize the heating energy increase under the economizer cycle by reducing the humidity requirements during the non-cooling seasons.

Table 4. Monthly Heating and Cooling Energy for Interior Systems Base Case

Month	Heating Energy Btu x 10^9	Cooling Energy Btu x 10^9
1	1.2334	.0739
2	1.0261	.0757
3	.7984	.2637
4	.6067	.5715
5	.5879	.9745
6	.5426	1.4150
7	.5436	1.9360
8	.5378	1.7190
9	.5582	1.4040
10	.6271	.6986
11	.7081	.3448
12	.9622	.0942
Yearly Total	8.7321	9.5709

Table 5. Monthly Heating & Cooling Energy for North Perimeter Systems Base Case

Month	Heating Energy Btu x 10^9	Cooling Energy Btu x 10^9
1	.3366	.0032
2	.2757	.0037
3	.1799	.0221
4	.0776	.0668
5	.0352	.1402
6	.0121	.2335
7	.0063	.3454
8	.0079	.2995
9	.0178	.2301
10	.0699	.0825
11	.1488	.0317
12	.2584	.0036
Yearly Total	1.4262	1.4583

Table 6. Monthly Heating & Cooling Energy for South Perimeter Systems Base Case

Month	Heating Energy Btu x 10^9	Cooling Energy Btu x 10^9
1	.3543	.0053
2	.2918	.0061
3	.1901	.0321
4	.0903	.0889
5	.0530	.1772
6	.0249	.2858
7	.0190	.4165
8	.0141	.3663
9	.0259	.2844
10	.0729	.1125
11	.1534	.0253
12	.2713	.0065
Yearly Total	1.5540	1.8269

Table 7. Monthly Energy Consumption for the Building Base Case

Month	Heating Energy Btu x 10^9	Cooling Energy Btu x 10^9	Fan Energy Btu x 10^9
1	1.9246	.0825	.2581
2	1.5935	.0855	.2396
3	1.1682	.3180	.2581
4	.7747	.7272	.2498
5	.6760	1.2919	.2581
6	.5796	1.9344	.2498
7	.5619	2.6976	.2581
8	.5599	2.3852	.2581
9	.6019	1.9138	.2498
10	.7703	.8936	.2581
11	1.0102	.4219	.2498
12	1.4919	.1043	.2581
Total	11.7127	12.8560	3.0455

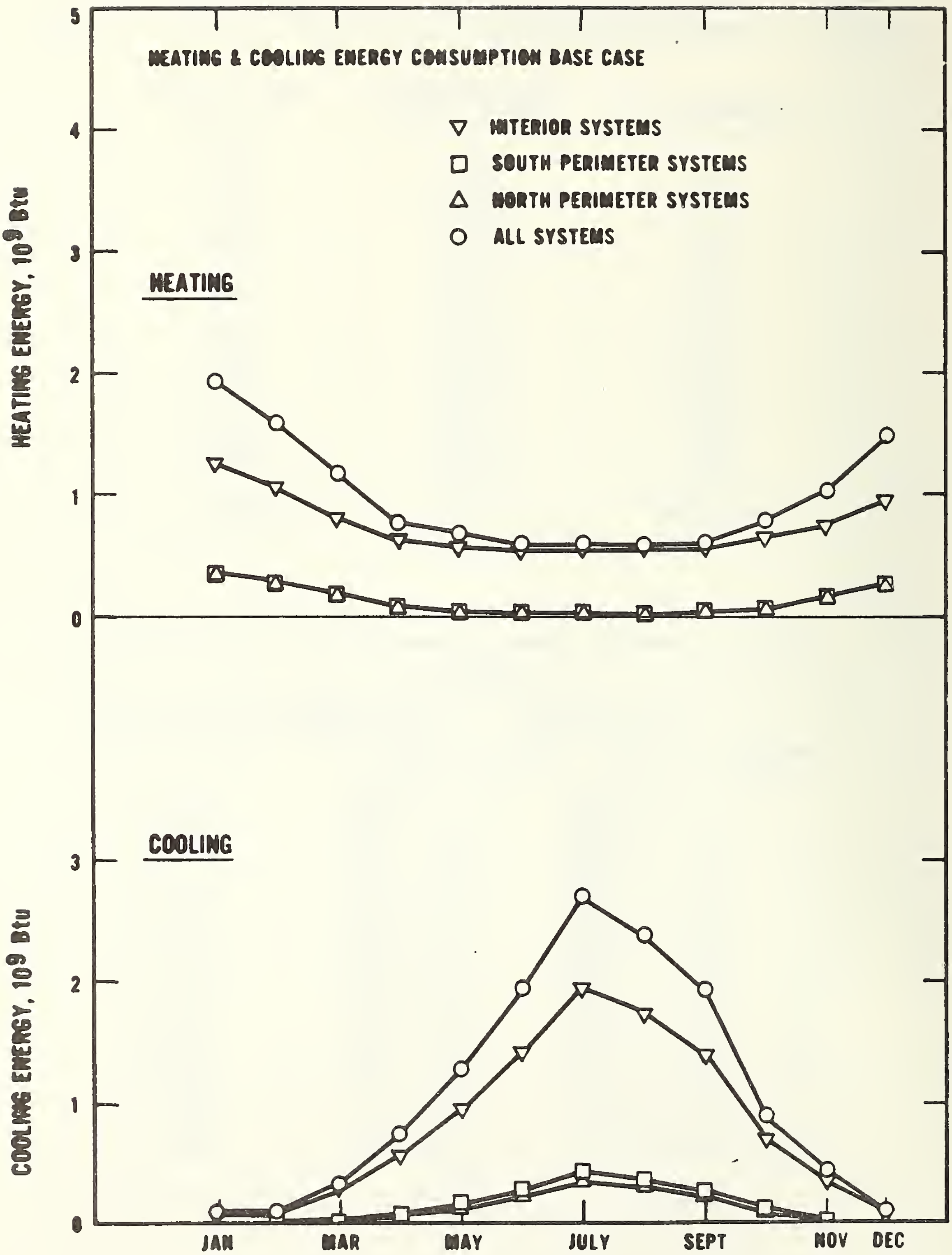


Figure 6. Heating and cooling energy consumption--base case

Table 8. Yearly Energy Consumption of Various Control Strategies

Cases	Heating Energy Btu x 10^9	Cooling Energy Btu x 10^9	Fan Energy Btu x 10^9
1. Base case	11.71	12.86	3.04
2. Same as base case, except, 65°F supply air temperature in winter for perimeter systems	11.57	12.68	3.04
3. Dry-bulb economizer for all systems	12.36	11.33	3.04
4. Same as 2, adding dry-bulb economizer for all systems	12.21	11.23	3.04
5. Enthalpy economizer for perimeter systems	11.77	12.54	3.04
6. Enthalpy economizer for all systems	12.37	11.01	3.04
7. Perimeter system supply air temperature reset from outside air temperature: 65°F at 65°F, 60°F at 66°F	11.58	12.36	3.04
8. Same as 7 except, 65°F at 40°F, 60°F at 80°F	11.51	12.38	3.04
9. ACU #6 and toilet exhaust fans off during non-office hours	11.68	12.43	2.79
10. ACU #3 and 6 off, toilet exhaust fan off, ACU's #5 and 8 on 100 percent OA during non-office hours	11.62	12.43	2.52
11. ACU's #3, 6 and 8 off, toilet exhaust fans off, ACU #5 on 100 percent OA during non-office hours	11.88	11.87	2.32
12. Interior systems on VAV	11.15	11.32	2.48
13. Interior systems on VAV and enthalpy economizer	11.50	10.32	2.48
14. Interior system supply air temperature reset between 50°F and 60°F by zone demand	10.65	11.13	3.04
15. Same as 14 except 50°F-60°F between May 1 and Sept. 30, 50°F-70°F between Oct. 1 and April 30	10.53	10.93	3.04
16. Same as 14, adding enthalpy economizer for all systems	11.08	9.65	3.04
17. Same as 15, adding enthalpy economizer for all systems	10.89	9.56	3.04
18. Perimeter system supply air temperature reset from outside air temperature, 65°F at 65°F, 60°F at 66°F; ACU #6 and exhaust fans off during non-office hours; interior system supply air temperature reset by zone demand, 50°F-60°F; enthalpy economizer for all systems	10.85	9.18	2.79
19. Same as 18, changing perimeter system supply air temperature reset from outside air temperature 65°F at 40°F and 60°F at 80°F	10.79	9.12	2.79
20. Base case with double-glazed windows	11.42	12.83	3.04

Table 9. Yearly Energy Consumption Comparison of Various Control Strategies

Cases	Heating Energy Btu x 10^9	Cooling Energy Btu x 10^9	Fan Energy Btu x 10^9
1. Base case	1.00	1.00	1.00
2. Same as base case, except, 65°F supply air temperature in winter for perimeter systems	.99	.99	1.00
3. Dry-bulb economizer for all systems	1.06	.88	1.00
4. Same as 2, adding dry-bulb economizer for all systems	1.04	.87	1.00
5. Enthalpy economizer for perimeter systems	1.01	.98	1.00
6. Enthalpy economizer for all systems	1.06	.86	1.00
7. Perimeter system supply air temperature reset from outside air temperature: 65°F at 65°F, 60°F at 66°F	.99	.96	1.00
8. Same as 7 except, 65°F at 40°F, 60°F at 80°F	.98	.96	1.00
9. ACU #6 and toilet exhaust fans off during non-office hours	1.00	.97	.83
10. ACU #3 and 6 off, toilet exhaust fan off, ACU's #5 and 8 on 100 percent OA during non-office hours	.99	.97	.83
11. ACU's #3, 6 and 8 off, toilet exhaust fans off, ACU #5 on 100 percent OA during non-office hours	1.01	.92	.76
12. Interior systems on VAV	.95	.88	.82
13. Interior systems on VAV and enthalpy economizer	.98	.80	.82
14. Interior system supply air temperature reset between 50°F and 60°F by zone demand	.91	.87	1.00
15. Same as 14 except 50°F-60°F between May 1 and Sept. 30, 50°F-70°F between Oct. 1 and April 30	.90	.85	1.00
16. Same as 14, adding enthalpy economizer for all systems	.95	.75	1.00
17. Same as 15, adding enthalpy economizer for all systems	.93	.74	1.00
18. Perimeter system supply air temperature reset from outside air temperature, 65°F at 65°F, 60°F at 66°F; ACU #6 and exhaust fans off during non-office hours; interior system supply air temperature reset by zone demand, 50°F-60°F; enthalpy economizer for all systems	.93	.71	.92
19. Same as 18, changing perimeter system supply air temperature reset from outside air temperature 65°F at 40°F and 60°F at 80°F	.92	.71	.92
20. Base case with double-glazed windows	.98	1.00	1.00

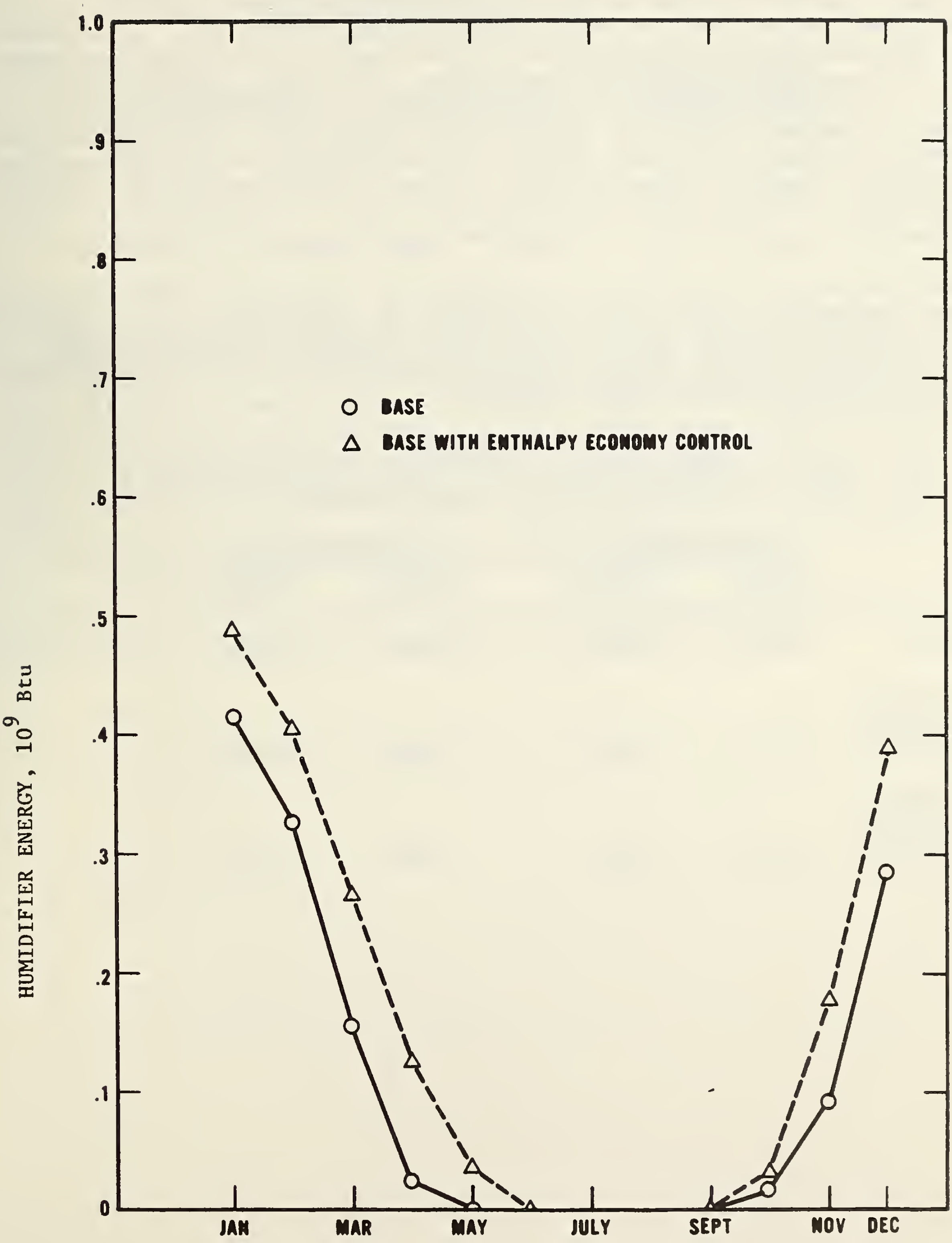


Figure 7. Comparison of humidifer energy consumption

The energy reductions for the perimeter system shutdown cases (cases 9, 10, and 11, and other combinations) are smaller than one would anticipate. As discussed in the previous section, the techniques modeled assumed the air-handling system outside air equaled the exhaust fan capacities. This is not completely true in reality. When some perimeter systems are turned off, the building is starved for air, but it "balances" itself by increasing air infiltration, increasing outside air coming into the air-handling systems, and reducing the exhaust air quantities. Therefore, the results of cases 9, 10, 11, 18, and 19 are conservative. Without measured data on air quantities during shutdown cases, it is difficult to judge quantitatively the additional energy savings caused by the reduced exhaust.

Although the overall building energy reduction, in percentage, is small for the perimeter temperature reset option, the savings on a system basis are substantial. Table 10 shows the yearly energy consumptions of the north and south systems and table 11 shows the percentage energy savings compared to the base case for the north, south, and the combined systems.

Table 10. Annual Heating and Cooling Energy for Perimeter System Supply Air Temperature Reset

	North Systems		South Systems	
	Heating 10^9 Btu	Cooling 10^9 Btu	Heating 10^9 Btu	Cooling 10^9 Btu
Base Case	1.4262	1.4583	1.5540	1.8269
Case 7 Reset, 65°F at 65°F, 60°F at 66°F	1.3625	1.2481	1.4880	1.5392
Case 8 Reset 65°F at 40°F, 60°F at 80°F	1.3340	1.2572	1.4463	1.5570

Table 11. Annual Savings for Perimeter System Supply Air Temperature Reset

	North Systems		South Systems		North and South Systems Combined	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
Case 7	4.5%	14.4%	4.2%	15.7%	4.4%	15.2%
Case 8	6.5%	13.8%	6.9%	14.8%	6.7%	14.3%

Table 11 shows that over 4 percent in heating energy and over 14 percent in cooling energy savings may be obtained by either of these temperature resets. These savings result from shaving the unnecessary cooling capacities during the part-load conditions to match closer to the space loads. It is interesting to note that when the strategies are combined, the overall saving trends may not agree with those of the individual strategies. For the perimeter system supply air temperature reset cases, case 7 (65° at 65°F and 60°F at 66°F) saves more than case 8 (65°F at 40°F and 60°F at 80°F) in heating but saves less in cooling. When the same resets are applied with other strategies, as in cases 18 and 19, the savings of both heating and cooling favor case 19.

It is obvious from tables 8 and 9 that installing double-glazed windows in this building is hardly a viable retrofit option for energy conservation.

5. CONCLUSION

Ranking of the control strategies investigated in this report is not feasible, since that would require the investigation of the efficiencies of the heating and cooling plants and the fuel costs for their generation, which would go beyond the boundaries of this building and the scope of this report (see Preface). From the individual heating, cooling, and fan energy consumptions of this building, the following conclusions are stated:

1. All of the basic control strategies (case 20 is not considered a control strategy) should save considerable amounts of energy, even though the percentage of savings of some of the strategies to the total building consumption are small. The costs for control strategy modifications seem minimal.

2. Both dry-bulb and enthalpy economizer cycles are energy saving controls. The enthalpy type has a two percent saving edge in cooling over the dry-bulb type. The heating energy increase caused by these controls may be reduced, if the minimum indoor humidity requirement during the non-cooling seasons is reduced.

3. The overall building energy reduction from the perimeter system supply air temperature reset by outdoor temperature is relatively small (four percent).

4. The energy reduction from perimeter system shutdowns may save a considerable amount of energy. The actual savings should be larger than those predicted here.

5. The largest energy saving should be possible with the interior systems. Resetting interior system supply air temperature by zone demand saves slightly (three percent in cooling and five percent in heating) more than converting to VAV system, fan energy savings from VAV being ignored.

6. Annual energy savings of 0.29×10^9 Btu in heating, 3.66×10^9 Btu in cooling and 0.25×10^9 Btu in fan operation may be achieved by combining various control strategies (case 19). This amounts to eight percent, twenty-nine percent, and eight percent in heating, cooling and fan energy savings, respectively, as compared to the base case.

Obviously, it must be emphasized that these conclusions are drawn from the results for this particular laboratory building under the Washington, D.C. weather conditions.

REFERENCES

1. Hoffman, J.D., "Energy Conservation at the NBS Laboratories," NBSIR 74-593, 1974.

2. Conversation with Chris Conley of NBS Plant Division, October 1980.

3. "Emergency Building Temperature Restrictions," Federal Register, Volume 44, Number 130, Thursday, July 5, 1979, pp. 39354-39369.

4. Hittle, D.C., The Building Loads Analysis and System Thermodynamics (BLAST) Program, Version 2.0: Users Manual, Volume I, U.S. Army Construction Engineering Research Laboratory, 1979. Available from NTIS, Springfield, VA. 22151.

APPENDIX

Input Data for Base Case

1. INTRODUCTION

This appendix is presented here for the readers who are familiar with the BLAST-2 program applications and wish to examine how the building and the air-handling system control details for the base case were handled. Specific modelling methods and other control strategies are as described in the text.

2. INPUT DATA

```
        BEGIN INPUT;
        RUN CONTROL?
          NEW ZONES,
          NEW AIR SYSTEMS,
          CENTRAL PLANT,
          UNITS(IN=ENGLISH,OUT=ENGLISH);
        DEFINE LOCATION?
          WASHING=
          (LAT= 38.85,LONG= 77.03,TZ= 5);
          END LOCATION;
        DEFINE DESIGN DAYS?
          DD1=(HIGH=91,LOW=71,WB=77, DATE=21 JUL);
          END DESIGN DAYS;
        DEFINE SCHEDULE (NBS PEOPLE)?
          MONDAY THRU FRIDAY   =(21 TO  5 - 0.0, .1,.1,.2,.8,
                                  9 TO 12 - 1.0, .8,
                                 13 TO 17 - 1.0, .6,.2,.1,.1),
          SATURDAY THRU SUNDAY =( 0 TO 24 - 0.0), HOLIDAY=SUNDAY;
          END SCHEDULE;
        DEFINE SCHEDULE (NBS LIGHTS)?
          MONDAY THRU FRIDAY   =(18 TO  8 - 0.2, .5,
                                  9 TO 18 - 1.0),
          SATURDAY THRU SUNDAY =( 0 TO 24 - 0.2), HOLIDAY=SUNDAY;
          END SCHEDULE;
        DEFINE SCHEDULE (NBS ELECTRIC EQUIPMENT)?
          MONDAY THRU FRIDAY   =(18 TO  9 - 0.2,
                                  9 TO 16 - 1.0,0.4,0.2),
          SATURDAY THRU SUNDAY =( 0 TO 24 - 0.2), HOLIDAY=SUNDAY;
          END SCHEDULE;
        DEFINE CONTROLS(GENERAL LAB)?         **SA=57, REHEAT=65
          PROFILES?
            P7=(1.0 AT 64, 0.0 AT 65, -0.286 AT 65, -1.0 AT 85);
          SCHEDULES?
            SUNDAY THRU SATURDAY = (00 TO 24 - P7), HOLIDAY=SUNDAY;
          END CONTROLS;
        DEFINE CONTROLS(CRITICAL LAB)?        **SA=57, REHEAT=72
          PROFILES?
            P8=(1.0 AT 71.5, 0.0 AT 72, -0.536 AT 72, -1.0 AT 85);
          SCHEDULES?
            SUNDAY THRU SATURDAY = (00 TO 24 - P8), HOLIDAY=SUNDAY;
          END CONTROLS;
        DEFINE CONTROLS(OFFICE SIXTY)?        **SA=60
          PROFILES?
            P10=(1.0 AT 64, 0.0 AT 65, -0.2 AT 65, -1.0 AT 85);
          SCHEDULES?
            SUNDAY THRU SATURDAY = (00 TO 24 - P10), HOLIDAY=SUNDAY;
          END CONTROLS;
        DEFINE MATERIALS?
  ACOUSTIC TILE=
    (L=0.0625,K=0.033,D=20.0,CP=0.2);
  AIRSPACE VERTICAL=
    (R=1.01,AIR);
  FACE BRICK=
    (L=0.3229,K=0.75,D=130.0,CP=0.2);
  CONC 6=
    (L=0.5000,K=1.0,D=140.0,CP=0.2);
  CONC 8=
    (L=0.6667,K=1.0,D=140.0,CP=0.2);
  FLOOR TILE=
    (R=0.05);
  GYP BOARD=
    (L=0.0417,K=0.0938,D=50.0,CP=0.2);
  METAL ROOF DECK=
    (L=0.0052,K=26.2,D=489.0,CP=0.12);
  METAL WALL SKIN=
```

```
  (L=0.0052,K=26.2,D=489.0,CP=0.12);
MOCK EARTH R10=
  (L=1.0,K=0.100,D=100.0,CP=0.2);
MOCK EARTH THICK=
  (R=100.0);
PLATE GLASS 1-4 CLEAR=
  (R=0.048,GLASS,TRANS=.80,VERY SMOOTH);
RIGID INS 1.5=
  (L=0.125,K=0.027,D=15.0,CP=0.17);
BUILT UP ROOFING=
  (L=0.0313,K=0.094,D=70.0,CP=0.35,VERY ROUGH);
ROOF INS=
  (R=8.0);
VENETIAN BLIND=
  (R=0.00004,SHADE,TRANS=0.18,ABS=0.40,REF=0.42);
        END MATERIALS;
      DEFINE WALLS?
BRICK WALL=
  (FACE BRICK,
   AIRSPACE VERTICAL,
   CONC 8,
   AIRSPACE VERTICAL,
   METAL WALL SKIN);
CONC DIAGONAL WALL=
  (CONC 8);
CURTAIN WALL INS PANEL=
  (METAL WALL SKIN,
   RIGID INS 1.5,
   METAL WALL SKIN);
LAB WALL=
  (METAL WALL SKIN,
   AIRSPACE VERTICAL,
   METAL WALL SKIN);
OFFICE WALL=
  (METAL WALL SKIN,
   GYP BOARD,
   METAL WALL SKIN,
   AIRSPACE VERTICAL,
   METAL WALL SKIN,
   GYP BOARD,
   METAL WALL SKIN);
        END WALLS;
      DEFINE ROOFS?
FLAT ROOF INS=
  (BUILT UP ROOFING,
   ROOF INS,
   METAL ROOF DECK);
FLOOR-CEILING ATTIC=
  (CONC 6,
   ACOUSTIC TILE);
MIDDLE FLOOR-CEILING=
  (FLOOR TILE,
   CONC 6);
        END ROOFS;
      DEFINE FLOORS?
FLOOR ATTIC=
  (ACOUSTIC TILE,
   CONC 6);
MIDDLE FLOOR=
  (CONC 6,
   FLOOR TILE);
INTERIOR GROUND FLOOR=
  (MOCK EARTH THICK,
   CONC 6);
PERIMETER GROUND FLOOR=
  (MOCK EARTH R10,
```

```
     CONC 6);
          END FLOORS;
        DEFINE WINDOWS?
SINGLE PANE GLASS=
  (PLATE GLASS 1-4 CLEAR,
   VENETIAN BLIND);
          END WINDOWS;
        PROJECT=$JK47Z   NBS GP LAB AND OFFICE, BLDG 223$;
          LOCATION=WASHING;
          GROUND TEMPERATURES=(60,60,60,60,60,68,68,68,68,60,60,60);
          DESIGN DAYS=DD1;
          $$WEATHER TAPE FROM 01 JAN 79 THRU 31 DEC 79;
        BEGIN BUILDING DESCRIPTION;
          NORTH AXIS=0;
        ATTIC 1 $ATTIC$?
          NORTH AXIS=0;
        EXTERIOR WALLS?
STARTING AT (383,103,0) FACING (0)
CURTAIN WALL INS PANEL (383 BY 12)
,
STARTING AT (383,0,0) FACING (90)
CURTAIN WALL INS PANEL (103 BY 12)
,
STARTING AT (0,0,0) FACING (180)
CURTAIN WALL INS PANEL (383 BY 12)
,
STARTING AT (0,103,0) FACING (270)
CURTAIN WALL INS PANEL (103 BY 12)
;
        PARTITIONS?
STARTING AT (87,13,24) FACING (0)
CONC DIAGONAL WALL (87 BY 12)
,
STARTING AT (87,0,24) FACING (90)
CONC DIAGONAL WALL (13 BY 12)
,
STARTING AT (383,0,0) FACING (15)
CONC DIAGONAL WALL (396 BY 12)
,
STARTING AT (0,0,0) FACING (165)
CONC DIAGONAL WALL (396 BY 12)
,
STARTING AT (0,103,0) FACING (195)
CONC DIAGONAL WALL (396 BY 12)
,
STARTING AT (383,103,0) FACING (345)
CONC DIAGONAL WALL (396 BY 12)
;
        ROOF?
STARTING AT (0,0,12) FACING (180)
FLAT ROOF INS (383 BY 103)
;
        ATTIC FLOOR?
STARTING AT (0,103,0) FACING (180)
FLOOR ATTIC (383 BY 103)
;
          END ZONE;
        ZONE 2 $LOWER GENERAL LABS$?
          NORTH AXIS =0;
          LIGHTS=5.460, NBS LIGHTS;
          PEOPLE=3.0, NBS PEOPLE;
          ELECTRIC EQUIPMENT=4.436, NBS ELECTRIC EQUIPMENT;
          CONTROLS=GENERAL LAB,      1000000 HEATING, 29.321 COOLING;
        PARTITIONS?
STARTING AT (11,24,0) FACING (0)
LAB WALL (11 BY 22.333)
```

```
,
STARTING AT (11,0,0) FACING (90)
LAB WALL (24 BY 22.333)
,
STARTING AT (0,0,0) FACING (180)
LAB WALL (11 BY 22.333)
,
STARTING AT (0,24,0) FACING (270)
LAB WALL (24 BY 22.333)
;
      CEILING?
STARTING AT (0,0,22.333) FACING (180)
MIDDLE FLOOR-CEILING (22 BY 24)
;
      SLAB ON GRADE FLOOR?
STARTING AT (0,24,0) FACING (180)
INTERIOR GROUND FLOOR (11 BY 24)
;
      FLOOR?
STARTING AT (0,24,0) FACING (180)
MIDDLE FLOOR (11 BY 24)
;
        END ZONE;
      ZONE 3 #UPPER GENERAL LAB#?
        NORTH AXIS =0;
        LIGHTS=2.730, NBS LIGHTS;
        PEOPLE=1.5, NBS PEOPLE;
        ELECTRIC EQUIPMENT=2.218, NBS ELECTRIC EQUIPMENT;
        CONTROLS=GENERAL LAB,      1000000 HEATING, 14.660 COOLING;
      PARTITIONS?
STARTING AT (11,24,0) FACING (0)
LAB WALL (11 BY 11.167)
,
STARTING AT (11,0,0) FACING (90)
LAB WALL (24 BY 11.167)
,
STARTING AT (0,0,0) FACING (180)
LAB WALL (11 BY 11.167)
,
STARTING AT (0,24,0) FACING (270)
LAB WALL (24 BY 11.167)
;
      CEILING UNDER ATTIC?
STARTING AT (0,0,24) FACING (180)
FLOOR-CEILING ATTIC (11 BY 24)
;
      FLOOR?
STARTING AT (0,24,0) FACING (180)
MIDDLE FLOOR (11 BY 24)
;
        END ZONE;
      ZONE 4 #LOWER CRITICAL LABS#?
        SAME AS ZONE 2 EXCEPT?
        CONTROLS=CRITICAL LAB,     1000000 HEATING, 29.321 COOLING;
        END ZONE;
      ZONE 5 #UPPER CRITICAL LAB#?
        SAME AS ZONE 3 EXCEPT?
        CONTROLS=CRITICAL LAB,     1000000 HEATING, 14.660 COOLING;
        END ZONE;
      ZONE 6 #LOWER OFFICES SIXTY SOUTH#?
        NORTH AXIS =0;
        LIGHTS=3.0, NBS LIGHTS;
        PEOPLE=3.0, NBS PEOPLE;
        ELECTRIC EQUIPMENT=0.3412, NBS ELECTRIC EQUIPMENT;
        CONTROLS=OFFICE SIXTY,     1000000 HEATING, 16.17  COOLING;
      EXTERIOR WALLS?
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STARTING AT (0,0,0) FACING (180)
BRICK WALL (11 BY 22.333)
WITH WINDOWS OF TYPE
SINGLE PANE GLASS (4.5 BY 16) AT (3,2.5)
;
      PARTITIONS?
STARTING AT (11,0,0) FACING (90)
OFFICE WALL (23 BY 22.333)
,
STARTING AT (11,23,0) FACING (0)
OFFICE WALL (11 BY 22.333)
,
STARTING AT (0,23,0) FACING (270)
OFFICE WALL (23 BY 22.333)
;
      CEILING?
STARTING AT (0,0,22.333) FACING (180)
MIDDLE FLOOR-CEILING (22 BY 23)
;
      SLAB ON GRADE FLOOR?
STARTING AT (0,23,0) FACING (180)
PERIMETER GROUND FLOOR (11 BY 23)
;
      FLOOR?
STARTING AT (0,23,0) FACING (180)
MIDDLE FLOOR (11 BY 23)
;
        END ZONE;
      ZONE 7 #UPPER OFFICE SIXTY SOUTH#?
        NORTH AXIS =0;
        LIGHTS=1.5, NBS LIGHTS;
        PEOPLE=1.5, NBS PEOPLE;
        ELECTRIC EQUIPMENT=0.1706, NBS ELECTRIC EQUIPMENT;
        CONTROLS=OFFICE SIXTY,     1000000 HEATING,  9.71  COOLING;
      EXTERIOR WALLS?
STARTING AT (0,0,0) FACING (180)
BRICK WALL (11 BY 11.667)
WITH WINDOWS OF TYPE
SINGLE PANE GLASS (4.5 BY 8) AT (3,2.5)
;
      PARTITIONS?
STARTING AT (11,0,0) FACING (90)
OFFICE WALL (23 BY 11.167)
,
STARTING AT (11,23,0) FACING (0)
OFFICE WALL (11 BY 11.167)
,
STARTING AT (0,23,0) FACING (270)
OFFICE WALL (23 BY 11.167)
;
      CEILING UNDER ATTIC?
STARTING AT (0,0,11.167) FACING (180)
FLOOR-CEILING ATTIC (11 BY 23)
;
      FLOOR?
STARTING AT (0,23,0) FACING (180)
MIDDLE FLOOR (11 BY 23)
;
        END ZONE;
      ZONE 8 #LOWER OFFICES SIXTY NORTH#?
        NORTH AXIS =180;
        SAME AS ZONE 6 EXCEPT?
        CONTROLS=OFFICE SIXTY,     1000000 HEATING, 11.72  COOLING;
        END ZONE;
      ZONE 9 #UPPER OFFICE SIXTY NORTH#?
        NORTH AXIS =180;
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      SAME AS ZONE 7 EXCEPT?
      CONTROLS=OFFICE SIXTY,     1000000 HEATING,  7.54  COOLING;
      END ZONE;
    END BUILDING DESCRIPTION;
    BEGIN FAN SYSTEM DESCRIPTION;
      VARIABLE VOLUME SYSTEM 20 ;INTERIOR 20; SERVING ZONE 2,3,4,5;
          **VAV BECAUSE IT-S AN OPTION TO BE TRIED
        FOR ZONE 2?  **LOWER FLOORS GENERAL PURPOSE LABS
          SUPPLY AIR VOLUME=  965.13;
          EXHAUST AIR VOLUME=  444.36;
          REHEAT CAPACITY=1000000;
          ZONE MULTIPLIER=28;
          END ZONE;
        FOR ZONE 3?  **TOP FLOOR GENERAL PURPOSE LAB
          SUPPLY AIR VOLUME=  482.57;
          EXHAUST AIR VOLUME=  222.18;
          REHEAT CAPACITY=1000000;
          ZONE MULTIPLIER=28;
          END ZONE;
        FOR ZONE 4?  **LOWER FLOORS CRITICAL LABS
          SUPPLY AIR VOLUME=  965.13;
          EXHAUST AIR VOLUME=  444.36;
          MINIMUM AIR FRACTION=1.0;
          REHEAT CAPACITY=1000000;
          ZONE MULTIPLIER=32;
          END ZONE;
        FOR ZONE 5?  **TOP FLOOR CRITICAL LAB
          SUPPLY AIR VOLUME=  482.57;
          EXHAUST AIR VOLUME=  222.18;
          MINIMUM AIR FRACTION=1.0;
          REHEAT CAPACITY=1000000;
          ZONE MULTIPLIER=32;
          END ZONE;
        OTHER SYSTEM PARAMETERS?
          HUMIDISTAT LOCATION=4;
          MIXED AIR CONTROL=FIXED PERCENT;
          HOT DECK TEMPERATURE=1000.0;
          COLD DECK TEMPERATURE=57.0;
          COLD DECK THROTTLING RANGE=1.0;
          SUPPLY FAN PRESSURE= 3.0;
          EXHAUST FAN PRESSURE=0.5;
          RETURN FAN PRESSURE= 1.25;
          SUPPLY FAN EFFICIENCY= 0.75;
          EXHAUST FAN EFFICIENCY=0.50;
          RETURN FAN EFFICIENCY= 0.70;
          HUMIDIFIER TYPE=STEAM;
          HUMIDISTAT SET POINT=30;
          PREHEAT COIL LOCATION=MIXED AIR DUCT;
          PREHEAT COIL CAPACITY=1000000;
          PREHEAT ENERGY SUPPLY=STEAM;
          WEEKDAY MINIMUM OUTSIDE AIR SCHEDULE=(0 TO 24 - 0.0);
          WEEKEND MINIMUM OUTSIDE AIR SCHEDULE=(0 TO 24 - 0.0);
          VAV MINIMUM AIR FRACTION=1.0;  **CONSTANT VOLUME
          VAV VOLUME CONTROL TYPE=INLET VANES;
          END OTHER SYSTEM PARAMETERS;
        EQUIPMENT SCHEDULES?
          SYSTEM OPERATION=INTERMITTENT;
          WEEKDAY SYSTEM SCHEDULE=(7 TO 18 - 1, 18 TO 7 - 1);
          WEEKEND SYSTEM SCHEDULE=(0 TO 24 - 1);
          END EQUIPMENT SCHEDULES;
        COOLING COIL DESIGN PARAMETERS?
          AIR VOLUME FLOW RATE=86862;
          WATER VOLUME FLOW RATE=77.107;
          ENTERING AIR DRY BULB TEMPERATURE=85;
          ENTERING AIR WET BULB TEMPERATURE=64;
          ENTERING WATER TEMPERATURE=42;
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          LEAVING AIR DRY BULB TEMPERATURE=54;
          LEAVING AIR WET BULB TEMPERATURE=53.3;
          LEAVING WATER TEMPERATURE=54;
          BAROMETRIC PRESSURE=405;
          AIR FACE VELOCITY=360;
          WATER VELOCITY=275;
          END COOLING COIL DESIGN PARAMETERS;
          END SYSTEM;
      VARIABLE VOLUME SYSTEM 3 #SOUTH EXTERIOR 3# SERVING ZONE 6,7;
        FOR ZONE 6?  **LOWER FLOORS
          SUPPLY AIR VOLUME=  596;
          EXHAUST AIR VOLUME= 246;
          REHEAT CAPACITY=1000000;
          ZONE MULTIPLIER=12;
          END ZONE;
        FOR ZONE 7?  **TOP FLOOR
          SUPPLY AIR VOLUME=  358;
          EXHAUST AIR VOLUME= 148;
          REHEAT CAPACITY=1000000;
          ZONE MULTIPLIER=12;
          END ZONE;
        OTHER SYSTEM PARAMETERS?
          HUMIDISTAT LOCATION=6;
          MIXED AIR CONTROL=FIXED PERCENT;
          COLD DECK TEMPERATURE=60.0;
          COLD DECK THROTTLING RANGE=1.0;
          SUPPLY FAN PRESSURE= 3.0;
          EXHAUST FAN PRESSURE=0.5;
          RETURN FAN PRESSURE= 1.25;
          SUPPLY FAN EFFICIENCY= 0.75;
          EXHAUST FAN EFFICIENCY=0.50;
          RETURN FAN EFFICIENCY= 0.70;
          HUMIDIFIER TYPE=STEAM;
          HUMIDISTAT SET POINT=30;
          PREHEAT COIL LOCATION=MIXED AIR DUCT;
          PREHEAT COIL CAPACITY=1000000;
          PREHEAT ENERGY SUPPLY=STEAM;
          WEEKDAY MINIMUM OUTSIDE AIR SCHEDULE=(0 TO 24 - 0.0);
          WEEKEND MINIMUM OUTSIDE AIR SCHEDULE=(0 TO 24 - 0.0);
          VAV MINIMUM AIR FRACTION=1.00;
          VAV VOLUME CONTROL TYPE=INLET VANES;
          END OTHER SYSTEM PARAMETERS;
        EQUIPMENT SCHEDULES?
          SYSTEM OPERATION=INTERMITTENT;
          WEEKDAY SYSTEM SCHEDULE=(7 TO 18 - 1, 18 TO 7 - 1);
          WEEKEND SYSTEM SCHEDULE=(0 TO 24 - 1);
          END EQUIPMENT SCHEDULES;
        COOLING COIL DESIGN PARAMETERS?
          AIR VOLUME FLOW RATE=11448;
          WATER VOLUME FLOW RATE=10.162;
          ENTERING AIR DRY BULB TEMPERATURE=85;
          ENTERING AIR WET BULB TEMPERATURE=64;
          ENTERING WATER TEMPERATURE=42;
          LEAVING AIR DRY BULB TEMPERATURE=54;
          LEAVING AIR WET BULB TEMPERATURE=53.3;
          LEAVING WATER TEMPERATURE=54;
          BAROMETRIC PRESSURE=405;
          AIR FACE VELOCITY=360;
          WATER VELOCITY=275;
          END COOLING COIL DESIGN PARAMETERS;
          END SYSTEM;
      VARIABLE VOLUME SYSTEM 5 #SOUTH EXTERIOR 5# SERVING ZONE 6,7;
        FOR ZONE 6?
          SUPPLY AIR VOLUME=  596;
          EXHAUST AIR VOLUME= 246;
          REHEAT CAPACITY=1000000;
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          ZONE MULTIPLIER=15;
          END ZONE;
        FOR ZONE 7?
          SUPPLY AIR VOLUME=  358;
          EXHAUST AIR VOLUME= 148;
          REHEAT CAPACITY=1000000;
          ZONE MULTIPLIER=15;
          END ZONE;
        OTHER SYSTEM PARAMETERS?
          HUMIDISTAT LOCATION=6;
          MIXED AIR CONTROL=FIXED PERCENT;
          COLD DECK TEMPERATURE=60.0;
          COLD DECK THROTTLING RANGE=1.0;
          SUPPLY FAN PRESSURE= 3.0;
          EXHAUST FAN PRESSURE=0.5;
          RETURN FAN PRESSURE= 1.25;
          SUPPLY FAN EFFICIENCY= 0.75;
          EXHAUST FAN EFFICIENCY=0.50;
          RETURN FAN EFFICIENCY= 0.70;
          HUMIDIFIER TYPE=STEAM;
          HUMIDISTAT SET POINT=30;
          PREHEAT COIL LOCATION=MIXED AIR DUCT;
          PREHEAT COIL CAPACITY=1000000;
          PREHEAT ENERGY SUPPLY=STEAM;
          WEEKDAY MINIMUM OUTSIDE AIR SCHEDULE=(0 TO 24 - 0.0);
          WEEKEND MINIMUM OUTSIDE AIR SCHEDULE=(0 TO 24 - 0.0);
          VAV MINIMUM AIR FRACTION=1.00;
          VAV VOLUME CONTROL TYPE=INLET VANES;
          END OTHER SYSTEM PARAMETERS;
        EQUIPMENT SCHEDULES?
          SYSTEM OPERATION=INTERMITTENT;
          WEEKDAY SYSTEM SCHEDULE=(7 TO 18 - 1, 18 TO 7 - 1);
          WEEKEND SYSTEM SCHEDULE=(0 TO 24 - 1);
          END EQUIPMENT SCHEDULES;
        COOLING COIL DESIGN PARAMETERS?
          AIR VOLUME FLOW RATE=14310;
          WATER VOLUME FLOW RATE=12.703;
          ENTERING AIR DRY BULB TEMPERATURE=85;
          ENTERING AIR WET BULB TEMPERATURE=64;
          ENTERING WATER TEMPERATURE=42;
          LEAVING AIR DRY BULB TEMPERATURE=54;
          LEAVING AIR WET BULB TEMPERATURE=53.3;
          LEAVING WATER TEMPERATURE=54;
          BAROMETRIC PRESSURE=405;
          AIR FACE VELOCITY=360;
          WATER VELOCITY=275;
          END COOLING COIL DESIGN PARAMETERS;
          END SYSTEM;
      VARIABLE VOLUME SYSTEM 6 $NORTH EXTERIOR 6$ SERVING ZONE 8,9;
        FOR ZONE 8?
          SUPPLY AIR VOLUME=  432;
          EXHAUST AIR VOLUME= 189;
          REHEAT CAPACITY=1000000;
          ZONE MULTIPLIER=16;
          END ZONE;
        FOR ZONE 9?
          SUPPLY AIR VOLUME=  278;
          EXHAUST AIR VOLUME= 122;
          REHEAT CAPACITY=1000000;
          ZONE MULTIPLIER=15;
          END ZONE;
        OTHER SYSTEM PARAMETERS?
          HUMIDISTAT LOCATION=8;
          MIXED AIR CONTROL=FIXED PERCENT;
          COLD DECK TEMPERATURE=60.0;
          COLD DECK THROTTLING RANGE=1.0;
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        SUPPLY FAN PRESSURE= 3.0;
        EXHAUST FAN PRESSURE=0.5;
        RETURN FAN PRESSURE= 1.25;
        SUPPLY FAN EFFICIENCY= 0.75;
        EXHAUST FAN EFFICIENCY=0.50;
        RETURN FAN EFFICIENCY= 0.70;
        HUMIDIFIER TYPE=STEAM;
        HUMIDISTAT SET POINT=30;
        PREHEAT COIL LOCATION=MIXED AIR DUCT;
        PREHEAT COIL CAPACITY=1000000;
        PREHEAT ENERGY SUPPLY=STEAM;
        WEEKDAY MINIMUM OUTSIDE AIR SCHEDULE=(0 TO 24 - 0.0);
        WEEKEND MINIMUM OUTSIDE AIR SCHEDULE=(0 TO 24 - 0.0);
        VAV MINIMUM AIR FRACTION=1.00;
        VAV VOLUME CONTROL TYPE=INLET VANES;
        END OTHER SYSTEM PARAMETERS;
      EQUIPMENT SCHEDULES:
        SYSTEM OPERATION=INTERMITTENT;
        WEEKDAY SYSTEM SCHEDULE=(7 TO 18 - 1, 18 TO 7 - 1);
        WEEKEND SYSTEM SCHEDULE=(0 TO 24 - 1);
        END EQUIPMENT SCHEDULES;
      COOLING COIL DESIGN PARAMETERS:
        AIR VOLUME FLOW RATE=11082;
        WATER VOLUME FLOW RATE= 9.837;
        ENTERING AIR DRY BULB TEMPERATURE=85;
        ENTERING AIR WET BULB TEMPERATURE=64;
        ENTERING WATER TEMPERATURE=42;
        LEAVING AIR DRY BULB TEMPERATURE=54;
        LEAVING AIR WET BULB TEMPERATURE=53.3;
        LEAVING WATER TEMPERATURE=54;
        BAROMETRIC PRESSURE=405;
        AIR FACE VELOCITY=360;
        WATER VELOCITY=275;
        END COOLING COIL DESIGN PARAMETERS;
        END SYSTEM;
    VARIABLE VOLUME SYSTEM 8 $NORTH EXTERIOR 8$ SERVING ZONE 8,9;
      FOR ZONE 8:
        SUPPLY AIR VOLUME=  432;
        EXHAUST AIR VOLUME= 189;
        REHEAT CAPACITY=1000000;
        ZONE MULTIPLIER=13;
        END ZONE;
      FOR ZONE 9:
        SUPPLY AIR VOLUME=  278;
        EXHAUST AIR VOLUME= 122;
        REHEAT CAPACITY=1000000;
        ZONE MULTIPLIER=12;
        END ZONE;
      OTHER SYSTEM PARAMETERS:
        HUMIDISTAT LOCATION=8;
        MIXED AIR CONTROL=FIXED PERCENT;
        COLD DECK TEMPERATURE=60.0;
        COLD DECK THROTTLING RANGE=1.0;
        SUPPLY FAN PRESSURE= 3.0;
        EXHAUST FAN PRESSURE=0.5;
        RETURN FAN PRESSURE= 1.25;
        SUPPLY FAN EFFICIENCY= 0.75;
        EXHAUST FAN EFFICIENCY=0.50;
        RETURN FAN EFFICIENCY= 0.70;
        HUMIDIFIER TYPE=STEAM;
        HUMIDISTAT SET POINT=30;
        PREHEAT COIL LOCATION=MIXED AIR DUCT;
        PREHEAT COIL CAPACITY=1000000;
        PREHEAT ENERGY SUPPLY=STEAM;
        WEEKDAY MINIMUM OUTSIDE AIR SCHEDULE=(0 TO 24 - 0.0);
        WEEKEND MINIMUM OUTSIDE AIR SCHEDULE=(0 TO 24 - 0.0);
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          VAV MINIMUM AIR FRACTION=1.00;
          VAV VOLUME CONTROL TYPE=INLET VANES;
          END OTHER SYSTEM PARAMETERS;
        EQUIPMENT SCHEDULES?
          SYSTEM OPERATION=INTERMITTENT;
          WEEKDAY SYSTEM SCHEDULE=(7 TO 18 - 1, 18 TO 7 - 1);
          WEEKEND SYSTEM SCHEDULE=(0 TO 24 - 1);
          END EQUIPMENT SCHEDULES;
        COOLING COIL DESIGN PARAMETERS?
          AIR VOLUME FLOW RATE=10290;
          WATER VOLUME FLOW RATE= 9.134;
          ENTERING AIR DRY BULB TEMPERATURE=85;
          ENTERING AIR WET BULB TEMPERATURE=64;
          ENTERING WATER TEMPERATURE=42;
          LEAVING AIR DRY BULB TEMPERATURE=54;
          LEAVING AIR WET BULB TEMPERATURE=53.3;
          LEAVING WATER TEMPERATURE=54;
          BAROMETRIC PRESSURE=405;
          AIR FACE VELOCITY=360;
          WATER VELOCITY=275;
          END COOLING COIL DESIGN PARAMETERS;
          END SYSTEM;
    END FAN SYSTEM DESCRIPTION;
    BEGIN CENTRAL PLANT DESCRIPTION;
      PLANT 1 #PLANT 1# SERVING SYSTEMS 3,5,6,8,20;
      EQUIPMENT SELECTION?
        1  BOILER  OF SIZE 5200.0;
        1  CHILLER OF SIZE 6800.0;
        END EQUIPMENT SELECTION;
        END PLANT;
    END CENTRAL PLANT DESCRIPTION;
    END INPUT;
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NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** *(See instructions)*	1. PUBLICATION OR REPORT NO. NBSIR 81-2277	2. Performing Organ. Report No.	3. Publication Date June 1981

4. TITLE AND SUBTITLE

Control Strategies for Energy Conservation, A Case Study of the Materials Building, National Bureau of Standards

5. AUTHOR(S)

James Y. Kao and E. Thomas Pierce

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

Final

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Plant Division
Office of the Director of Administrative and Information Systems
National Bureau of Standards
Washington, D.C. 20234

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The BLAST-2 Computer Program is used to investigate various heating, ventilating and air conditioning control strategies and their combinations to reduce the energy consumption of a laboratory building located at the National Bureau of Standards, Gaithersburg site. The techniques of modeling the building load and air system performance are explained. The results are presented and discussed. Control strategies investigated include dry-bulb and enthalpy economizer cycles, resetting supply air temperatures by outside temperature and zone demand, shutdown of fan systems selectively, and converting interior systems to VAV systems. By combining the various control strategies, eight percent, twenty-nine percent and eight percent of heating, cooling and fan energy respectively may be saved.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Building energy analysis, computer modeling, controls, control strategies, energy conservation for non-residential buildings, load calculations.

13. AVAILABILITY

☒ Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

115

15. Price

$11.00

USCOMM-DC 6043-P80